S29-34
N91-21091
2735
p-12

GRID GENERATION STRATEGIES FOR TURBOMACHINERY CONFIGURATIONS

K. D. Lee* and T. L. Henderson**
University of Illinois
Urbana, IL 61801

IB647432

ABSTRACT

Turbomachinery flow fields involve unique grid generation issues due to their geometrical and physical characteristics. Several strategic approaches are discussed to generate quality grids. The grid quality is further enhanced through blending and adapting. Grid blending smooths the grids locally through averaging and diffusion operators. Grid adaptation redistributes the grid points based on a grid quality assessment. These methods are demonstrated with several examples.

INTRODUCTION

Providing quality grids is a prerequisite for successful flow calculations. It is well known that most flow codes yield different solutions for the same problem with different grids. Therefore, for accurate solutions, grids should not only resolve geometric details of the configuration, but also accommodate characteristic features of the flow. In addition, grids should be compatible with particular solution algorithms in the flow code. As physical and geometrical complexities increase, it becomes more difficult to generate suitable grids.

Flow fields in propulsion systems often involve complicated geometries and exhibit complex flow phenomena. Internal flow fields are characterized by confined domains which may invoke more restrictive constraints and conflicting requirements in grid generation. Major difficulties involved with grid generation for turbomachinery configurations are attributed to the periodicity of the flow field and the close proximity of configuration elements. Moreover, some grid properties such as grid smoothness, grid orthogonality, and grid-flow alignment become very important in correctly capturing the physics of the flow field. The grid should be tailored to resolve flow features such as large thermal gradients, complicated shocks, and flow separations.

This paper addresses several issues arising in grid generation for turbomachinery configurations and discusses some grid generation strategies which can improve grid quality. Also considered are advantages and disadvantages of multi-block grid topologies and special grid arrangements at the periodic boundary. Then, two approaches which enhance grid quality are presented and demonstrated. One employs a local blending concept that enforces smoothness and continuity in grid properties. The other uses a grid adaptation procedure in which grid points are redistributed according to a grid quality measure. The latter is based on a grid adaptation technique developed to generate adaptive grids with respect to geometry, flow solution, and grid quality [1-3].

---

* Associate Professor, Aeronautical and Astronautical Engineering
** Graduate Research Assistant, Mechanical Engineering

GRID GENERATION ISSUES

The accuracy and efficiency of numerical solutions depend on certain properties of the grid used. Grid density determines the amount of truncation error in the flow calculation. Hence, grid points should be distributed following the flow physics to achieve the best possible accuracy while maintaining the same computational efficiency. This can be accomplished by using fine grids in high gradient regions and relatively coarse grids in slowly varying regions. An additional constraint is that the grid size should be at least the same order of magnitude as the characteristic length scales of the physics to be captured. Other grid properties also affect computational accuracy and economy. The resolution of discontinuities such as shock waves, contact surfaces, and dividing streamlines can best be accomplished with grids that are aligned with the discontinuities. Grid skewness, grid kinking, and grid stretching also affect the order of accuracy in spatial discretizations and strongly influence the convergence rate. In extreme cases, highly distorted grids may cause solution divergence. It is very difficult to generate a grid which is satisfactory in all respects, particularly when complex geometries are involved as in high-speed turbomachinery applications.

The primary difficulty for generating grids for high-speed turbomachinery stems from the confinement and periodicity of the flow domain. The presence of high thermal gradients and complicated shock structures makes the grid generation more difficult. It is desirable to cluster grid points and align grid lines along characteristics of the geometry and the flow in order to improve solution accuracy and numerical efficiency. However, improving one grid property may deteriorate other grid properties and grid enhancement in one region can cause conflicts with grid requirements in other regions. For example, a desirable grid density distribution may require sacrifices in grid properties such as grid orthogonality and smoothness. Grid orthogonality near the blade surface may also increase grid skewness elsewhere. These side effects become more significant when the turbomachinery geometry involves a small pitch angle, high angle of attack, and/or high camber.

Different flow codes impose different requirements on the grid quality. While some flow algorithms are more independent of grid characteristics, others place more stringent restrictions on the quality of the grid. Therefore, a careful balance must be obtained between the grid quality, solution algorithm, and flow physics. When these elements are not properly balanced, numerical errors may destroy important solution details or impair the convergence rate of the flow solver. This may occur to such an extent that the solution may not be useful. For example, many codes prefer that the grid be nearly orthogonal at domain boundaries for accurate implementations of boundary conditions. Another example can be found in the use of the thin-layer Navier-Stokes approximation. The approximation results in better accuracy with grids that have small variations in grid properties. Many higher-order upwind schemes also prefer smooth, well-aligned grids. Such additional restrictions underscore the importance of grid quality.

Since grid quality issues are often subject to conflicting requirements, suitable grids generally cannot be created in a single attempt. Grid generation involves negotiations and compromises between different grid characteristics. Usually grid quality is upgraded through an iterative grid adaptation process using grid quality assessments based on either experience or analysis. However, it is desirable to generate an initial grid that encompasses as many good qualities as possible in order to minimize efforts for improvement. This requires grid generation strategies which can accommodate anticipated flow characteristics and minimize conflicts between grid properties. Then a grid adaptation process can be applied to reduce the remaining deficiencies in grid properties. A systematic means of grid quality assessment can facilitate the grid modification process.

GRID GENERATION STRATEGIES

Three grid topologies are often used to generate grids around airfoil shapes: C-grid, O-grid, and H-grid. Different grid structures create different issues in grid generation and flow calculations. They each have their own advantages and disadvantages. These topologies are also used for turbine and compressor blades, as shown in Figure 1. The O-grid topology requires the least number of grid points to resolve the flow field near the blade surface, but exhibits difficulties in accommodating the confined and periodic features of turbomachinery. It is also difficult to align the grid lines with flow characteristic directions in the upstream and downstream regions. This problem can be resolved in the downstream side by using the C-grid topology. However, difficulties remain in aligning the grid lines with the periodic boundary and the flow direction in the upstream inflow region.

The H-grid structure is an alternative which is well suited to turbomachinery geometries because of its natural alignment with the periodic boundary, but the H-grid introduces other challenges. The H-grid structure raises different issues such as grid kinking across block boundaries and grid singularities at the leading and trailing edges. Figure 2 shows a typical grid for a turbine blade at a high angle of attack using the H-grid topology. Comparatively large cells or kinked grid lines can appear near the leading and trailing edges where rapid flow changes are expected. The grid becomes extremely skewed in the trailing edge region. This happens with all three grid topologies when the angle of attack or camber increases. The grid skewness may deteriorate the accuracy or cause instabilities in flow calculations.

One of the major issues in grid generation for turbomachinery is the grid skewness due to the presence of periodic boundaries. Two approaches are considered to improve grid qualities at the periodic boundary; grid slipping and index off-setting. Figure 3 shows a typical grid generated by allowing the grid lines to slip along the periodic boundary instead of matching them across the boundary. This eliminates the issue of grid skewness and kinkiness. It allows a family of grid lines to float along the boundary until they are orthogonal. Since grid lines no longer match across the periodic boundary, flow solvers should be furnished with an interpolation scheme to communicate across the boundary. The grid orthogonality at the boundary helps prevent losses in accuracy or convergence due to the interpolation. As seen in Figure 3, however, extremely large cells can appear near the periodic boundary when enforcing the orthogonal condition with a highly cambered blade. This presence of large cells can hurt the accuracy of the flow solution.

Another way to reduce grid skewness is to use index off-setting. This is a technique which allows grid lines with different indices to match across the periodic boundary. This allows the grid to be more orthogonal throughout the flow field while maintaining continuity across the periodic boundary. Figure 4 shows a typical example of index off-setting for a grid around a turbine blade. While no interpolation of flow variables is necessary, as in the case with grid line slipping, some additional bookkeeping is required to communicate across the boundary. In addition, a different number of grid points can be used on the leeward and windward sides of the blade. The grid in Figure 4 however uses the same number of grid points on both sides. The index off-setting strategy creates an irregularity at the farfield upstream and downstream boundaries, which may require additional care in handling multiple stage situations.

Grid quality can be further improved by combining different grid topologies. One example is the O-H grid structure. An O-grid is inserted into a H-grid, as shown in Figure 5. This combination can provide the advantages of the O-grid at the near field in accommodating the thermal and viscous boundary

layers. It can also provide the flexibility of the H-grid in the upstream and downstream regions. The grid skewness has been reduced by allowing grid lines to slip along the periodic boundary. The grid orthogonality near the blade has been improved, but many grid quality issues are still not resolved. The adoption of different grid strategies accompanies trade-offs. Enhancement of one grid property may cause deterioration in other aspects. All constraints cannot be resolved simultaneously and hence compromises should be reached. Therefore, the next step to improve grid quality is to use grid modifications after the initial grid generation.

GRID IMPROVEMENT BY BLENDING

The basic premise is that good quality grids usually cannot be obtained using a single-block grid structure for complex geometries. The grid quality can be improved by using a multiple block structure where the flow domain is divided into blocks and surface-fitted grids are generated in each block [4]. The H-grid and O-H grid structures in the previous section are examples of a multi-block grid. However, the multi-block structure introduces other concerns with respect to the grid quality. Without communication between blocks, grid lines can be kinked, and grid spacing can change abruptly across block boundaries. Communication between blocks is not always easy. Therefore it would be easier to improve the transition between blocks after the initial grid generation.

A natural approach to smoothing is to use blending. That is, the grid points in the neighborhood of a block boundary are relocated by using a diffusion operator. For example,

$$\vec{X}_t = \mu_1 \vec{X}_{\xi\xi} + \mu_2 \vec{X}_{\eta\eta} \tag{1}$$

where $\vec{X} = (x,y)$ denotes the physical coordinates of a grid point, and (ξ,η) are the grid indices of the computational domain. The parameters μ_1 and μ_2 are diffusion coefficients which determine the degree of blending. The time derivative in the left hand side implies the change of grid positions through blending. The blending can be applied in both implicit and explicit manners.

The blending can be extended into a more general form

$$\vec{X}_t = A_\eta D_\xi \mu_1 D_\xi \vec{X} + A_\xi D_\eta \mu_2 D_\eta \vec{X} \tag{2}$$

where A and D represent averaging and differential operators respectively with their subscripts indicating the direction of operation. Here, the diffusion coefficients μ_1 and μ_2 are no longer constants; they include weighting factors extracted from the initial grids. The weighting is defined to preserve the positive characteristics of the original grids.

The O-H grid shown in Figure 5 includes blending across the block boundaries. Figure 6 compares the grids before and after the blending in the leading and trailing edge regions. The inner O-grid is smoothly blended with the outer H-grid eliminating the grid kinking while maintaining basic grid spacing. The inner O-grid is nearly orthogonal to improve heat transfer and skin friction calculations. Improvements in grid quality can also be seen near the singular points where six cells join together, instead of regular four cells. The blending distributes the vertex angles more evenly and produces smoother grid transitions across block boundaries.

GRID IMPROVEMENT BY ADAPTATION

Grid quality can also be improved by using the adaptive grid generation technique presented in reference 3. In this approach, grid adaptation is achieved by numerically altering the mapping functions between the physical and computational spaces using grid control sources. Depending on how the control sources are defined, grids can be made adaptive to geometry, flow solution, or grid quality. The grid is adapted to grid quality in this work. Source strengths are extracted from the distribution of a grid quality parameter defined on the initial grid.

The grid adaptation procedure begins with a parametric representation of the initial grid which is obtained by normalizing its computational coordinates, or indices, into a unit square. The result is a uniformly discretized domain in parametric coordinates (s,t). This first mapping contains characteristics of the initial grid, which may already include grid controls with respect to geometry and flow solution.

The source strengths for grid control are formulated to reflect local grid characteristics. Two grid control sources are defined in each cell for separate control in each of the parametric directions. First, a monitor function ϕ is chosen which is a measure of some grid property. The source strengths can then be defined as linear combinations of the monitor function and its derivatives in each parametric coordinate. For example,

$$\begin{aligned} \sigma^s_{kl} &= w^s_0 \phi + w^s_1 \frac{\partial \phi}{\partial s} + w^s_2 \frac{\partial^2 \phi}{\partial s^2} \\ \sigma^t_{kl} &= w^t_0 \phi + w^t_1 \frac{\partial \phi}{\partial t} + w^t_2 \frac{\partial^2 \phi}{\partial t^2} \end{aligned} \tag{3}$$

where k and l are the indices of the cell containing the source. The w 's are input parameters which allow for different weights to be placed on the various derivatives of ϕ. Candidates for the monitor function, or grid quality parameter, include grid skewness, grid kinking, grid stretching, cell aspect ratio, cell volume, etc. A combination of different grid quality parameters can also be used.

A second mapping is obtained by including the influences of the grid control sources. This defines a modified set of parametric coordinates (s',t').

$$\begin{aligned} s'_{ij} &= s_{ij} + \sum_{k,l} K^s_{ijkl} \sigma^s_{kl} \\ t'_{ij} &= t_{ij} + \sum_{k,l} K^t_{ijkl} \sigma^t_{kl} \end{aligned} \tag{4}$$

where K^s_{ijkl} and K^t_{ijkl} are influence coefficients for the effects of a source (k,l) at a point (i,j). The coefficients are defined as exponentially decaying functions of the distance between the two points.

As a result of the second mapping, grid lines are displaced by the sources. The displacement is greatest in the regions of strong sources. The next step is to rediscretize the modified parametric domain. The physical locations of the new grid points are then obtained by an inverse mapping procedure from the parametric domain to the physical domain. As a result, the grid becomes adapted to the distribution of the chosen grid quality parameter. The adaptation process can be applied successively.

This method provides many desirable features through the use of the parametric mapping and grid control sources. For instance, the basic characteristics of the initial grid can be retained while adapting to grid quality. The grid control sources allow for linear combinations of different controls based on the superposition principle of potential theory. Thus, the grid can be made to adapt to more than one monitor function through a series of mappings. The source formulation also promotes smooth variations of the grid, even with nonsmooth, randomly distributed sources. If satisfactory results are not achieved after a single application, the adaptation process can be repeated in a cyclic manner.

Several examples are presented to demonstrate different applications of the grid adaptation technique. The first example concerns grid kinking at the periodic boundary. Figure 7 shows both the initial and adapted grids. The initial grid contains sharp grid kinking along the periodic boundary. This may create problems for many flow solvers. Large errors or severe stability limitations may occur. Therefore, grid kinking is used as the monitor function for the grid adaptation. Grid lines become smooth across the block boundary in the adapted grid, and the rest of the grid is virtually unchanged.

The second example improves the grid quality along the wake line of the grid shown in Figure 1c. Here, grids at the upper and lower sides of the wake line are generated as separate blocks, hence kinked grid lines appear across the wake. As shown in Figure 8, the adaptation smooths the grid lines across the wake without altering other grid properties.

The final example demonstrates the improvement of boundary orthogonality, as shown in Figure 9 for a H-grid around a cascade configuration. As discussed, boundary behavior of grid lines is especially important in viscous flow calculations for accurate predictions of skin friction and heat transfer rates. Therefore, orthogonal or near-orthogonal grids are sought near the blade. In this case, control sources are defined along the surface based on orthogonality. The adapted grid possesses good orthogonality near the surface and blends smoothly into the rest of the grid.

CONCLUSIONS

Grid generation is not an isolated, single-step process. Instead, an iterative feed-back cycle is required to reach an acceptable balance between different grid properties. Also, the grid should be able to conform to the geometry, to follow the flow characteristics, and be compatible with the specific solution algorithm. The interactions between the grid, flow physics, and solution algorithm will increase as the physical and geometrical complexities of the flow increase.

In this paper, various grid generation issues and grid quality requirements are discussed for high-speed turbomachinery flow calculations. The use of different grid generation strategies provides options for improving grid quality. Two grid modification approaches are presented to systematically correct undesirable grid properties. The examples presented demonstrate how significant improvements can be made through these approaches.

ACKNOWLEDGEMENTS

The authors wish to thank James Loellbach and James Hager of the University of Illinois for their assistance in preparing this paper. The support and encouragement of Dr. Raymond Cosner and Dr. August Verhoff of McDonnell Aircraft Company are also gratefully acknowledged. This work was partially funded by a contract under the Independent Research and Development Program of McDonnell Aircraft Company.

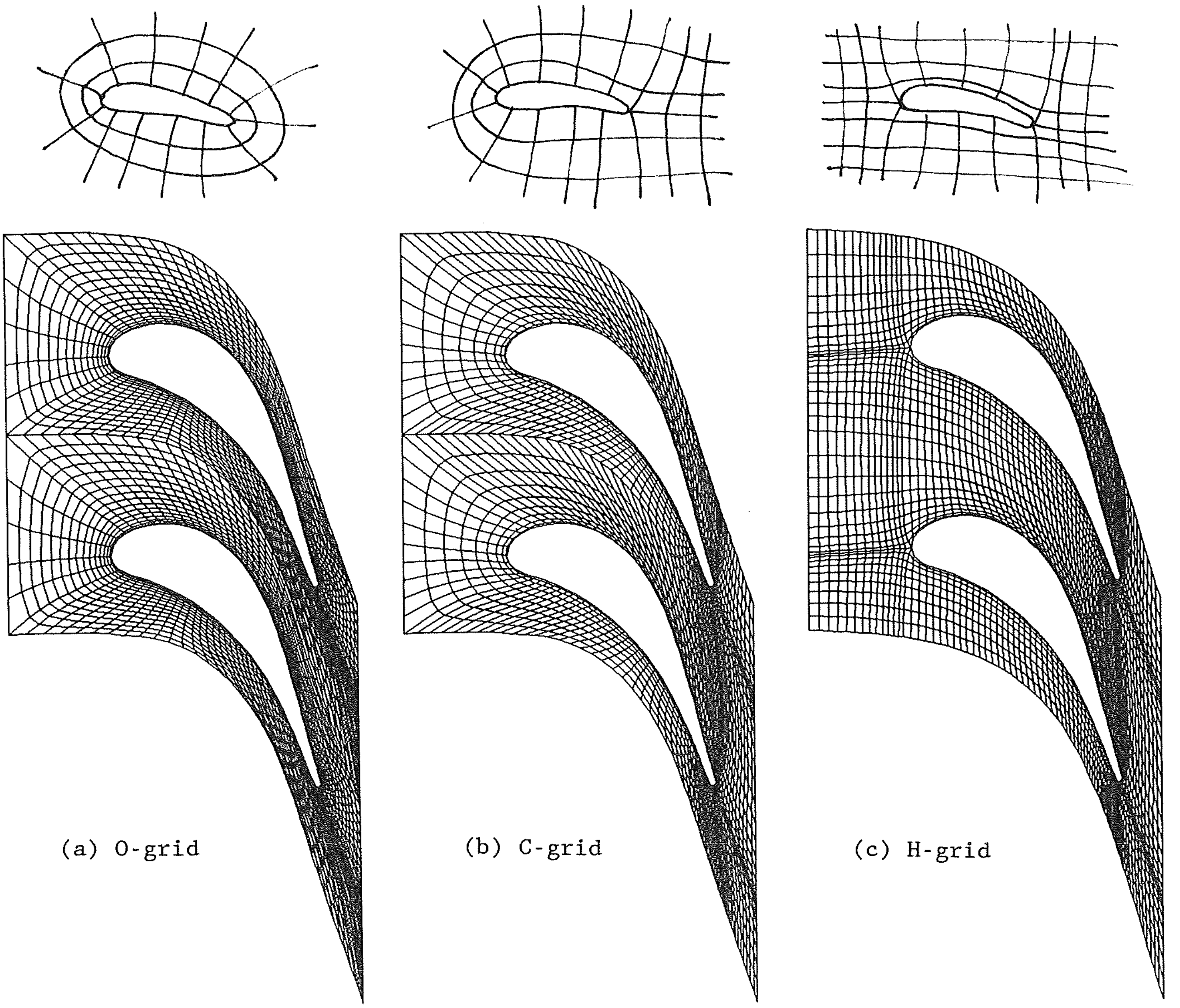
REFERENCES

1. Lee, K. D. and Loellbach, J. M., "Geometry-Adaptive Surface Grid Generation Using a Parametric Projection," *Journal of Aircraft*, 26, 162-167 (1989).

2. Lee, K. D. and Loellbach, J. M., "A Mapping Technique for Solution Adaptive Grid Control," AIAA Paper 89-2178, In *Proc. AIAA 7th Applied Aerodynamics Conference*, Seattle, WA, 129-139 (1989).

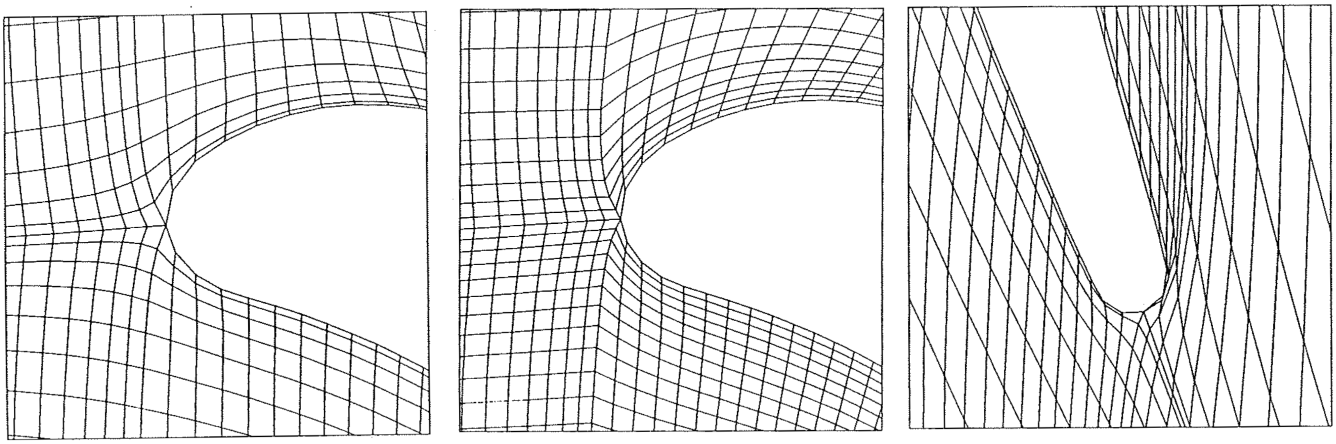
3. Lee, K. D., Loellbach, J. M., and Kim, M. S., "Adaptation of Structured Grids for Improved Navier-Stokes Solutions," AIAA Paper 90-0125 (1990).

4. Lee, K. D. and Rubbert, P. R., "Transonic Flow Calculation Using Grid Systems with Block Structure," In *Lecture Notes in Physics* 141, 266-271, Springer-Verlag (1980).



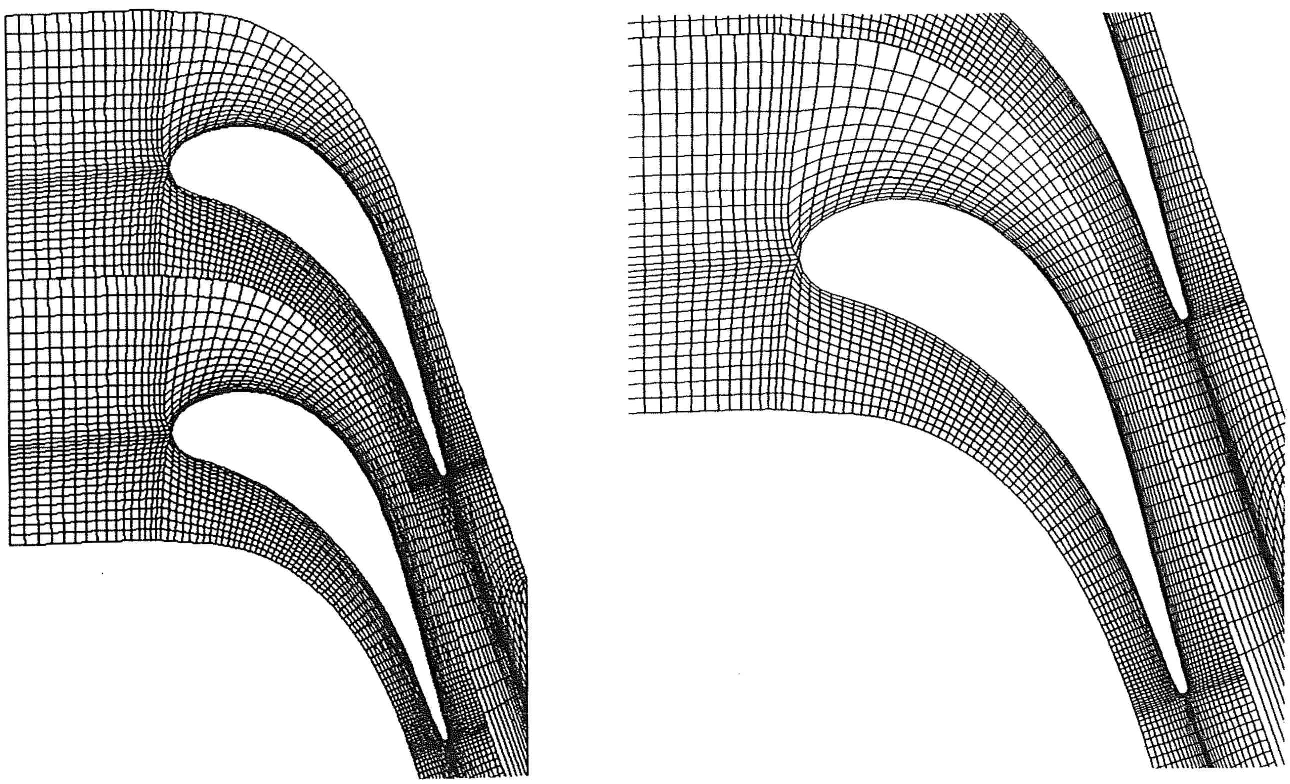
(a) O-grid (b) C-grid (c) H-grid

Figure 1. Examples of grid topologies for turbomachinery grids



(a) large LE cells (b) patched LE grids (c) skewed TE cells

Figure 2. H-grid details



(a) overall grid layout (b) near-field details

Figure 3. Grid line slipping at periodic boundary

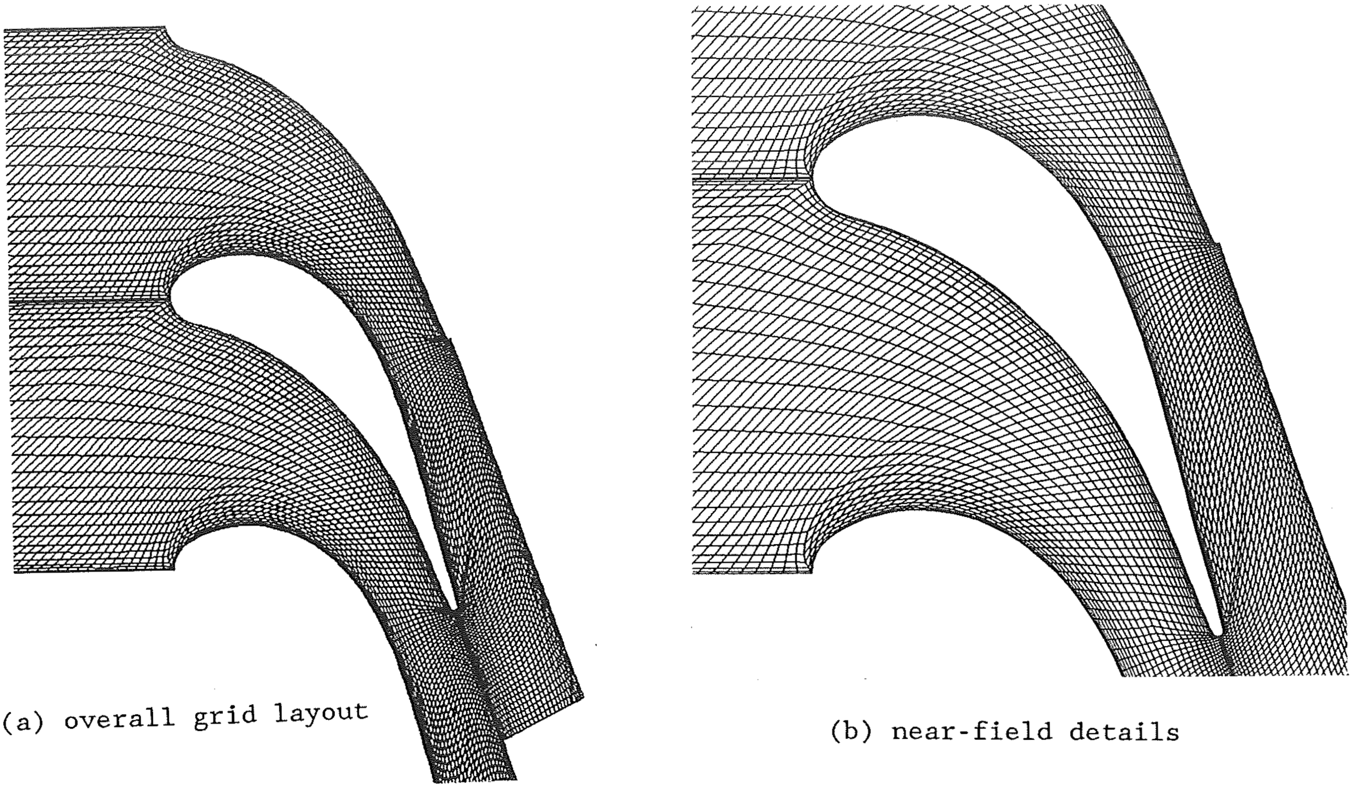


Figure 4. Index off-setting at periodic boundary

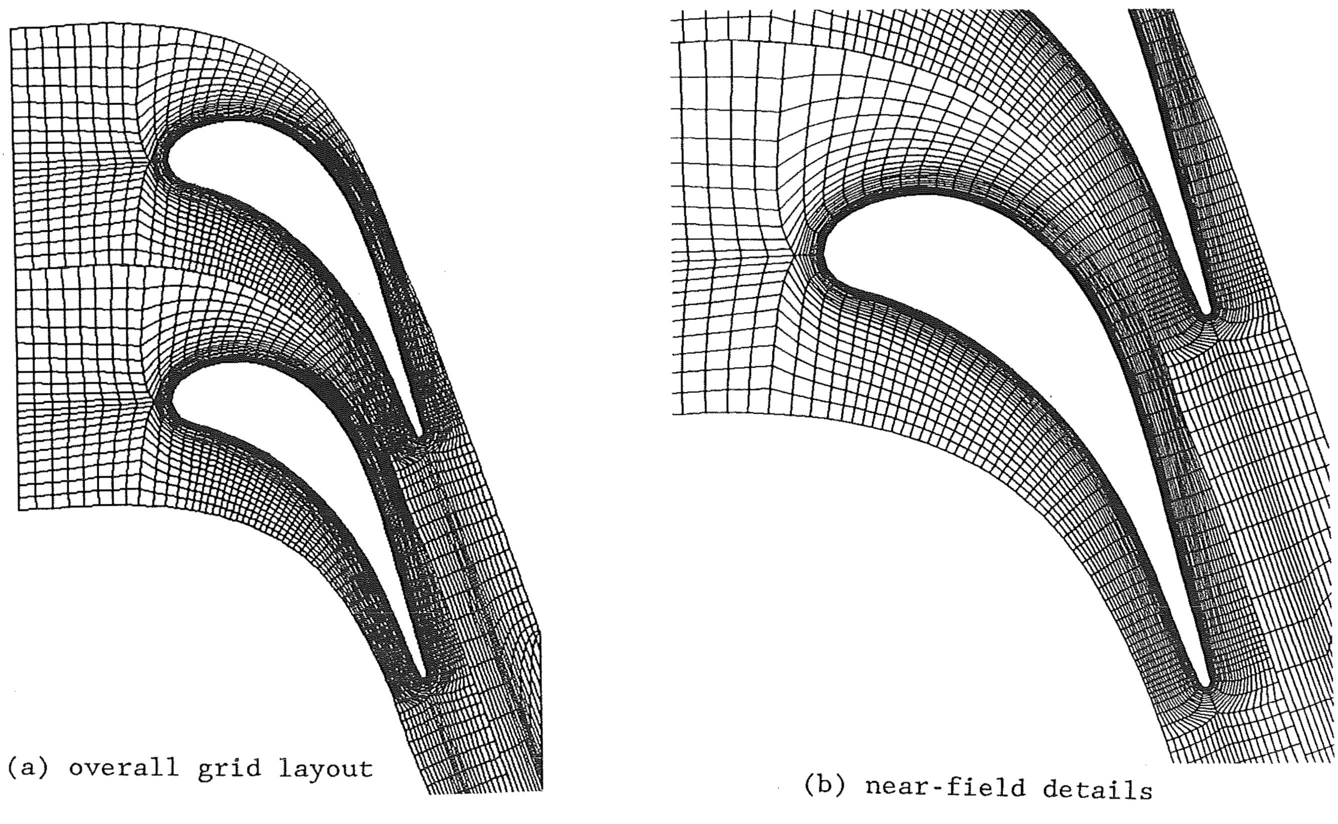
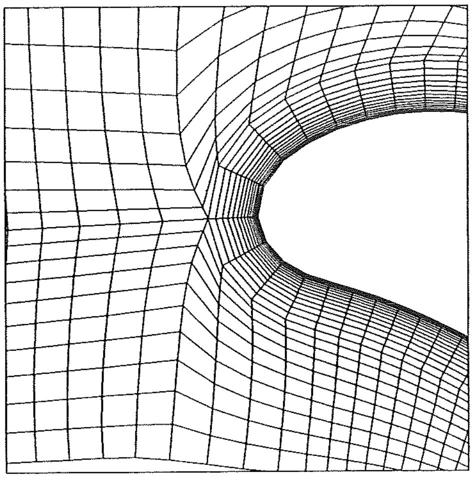
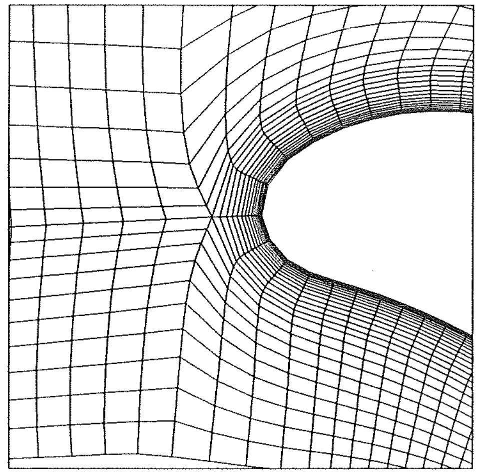


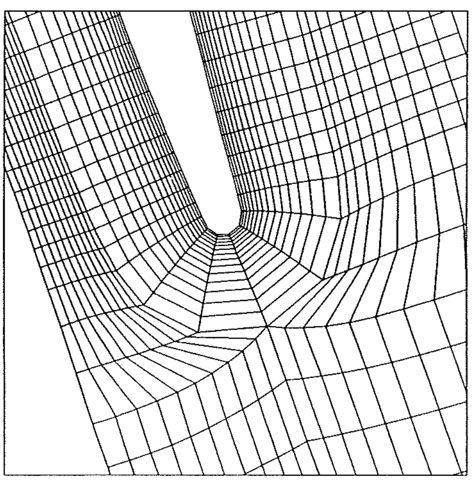
Figure 5. H-grid with O-grid insert



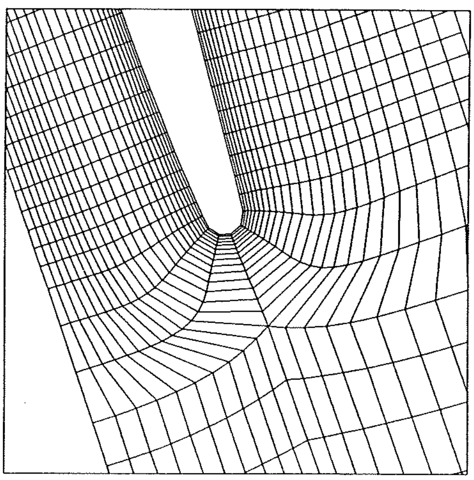
(a) LE grid before blending



(b) LE grid after blending

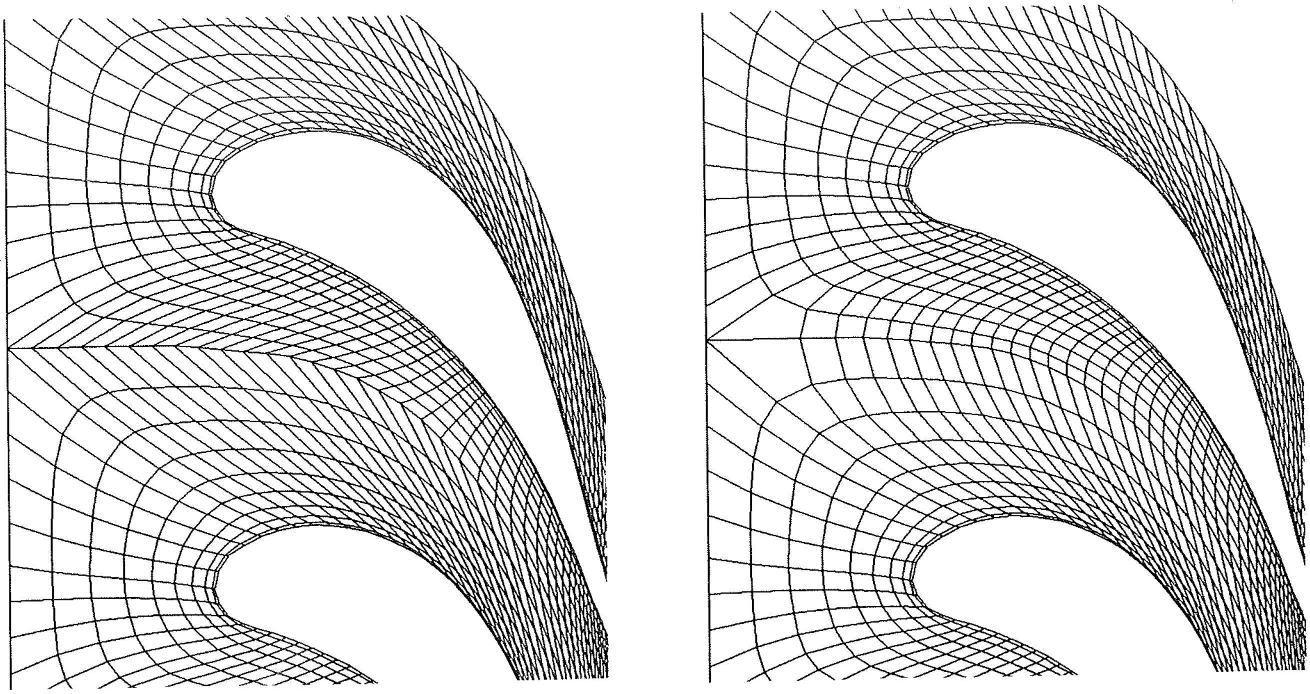


(c) TE grid before blending



(d) TE grid after blending

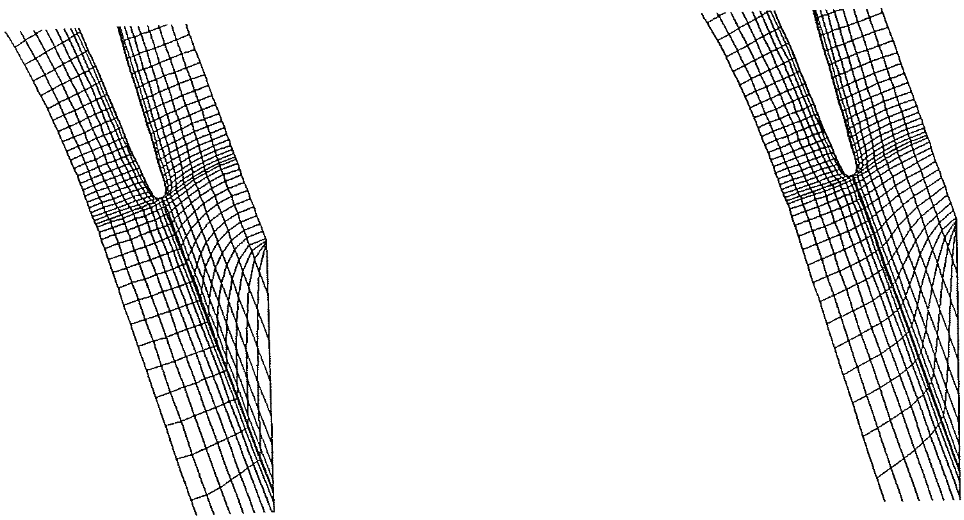
Figure 6. Blending across block boundaries for a O-H grid



(a) grid before adaptation

(b) grid after adaptation

Figure 7. Grid quality adaptation across periodic boundary - reduction of grid skewness

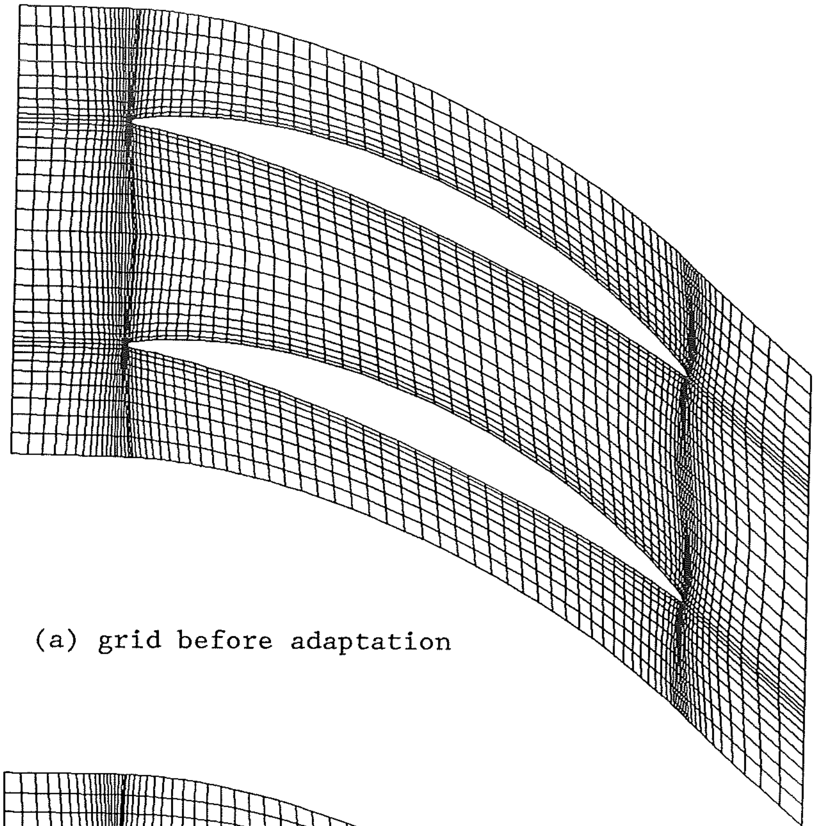


(a) grid before adaptation

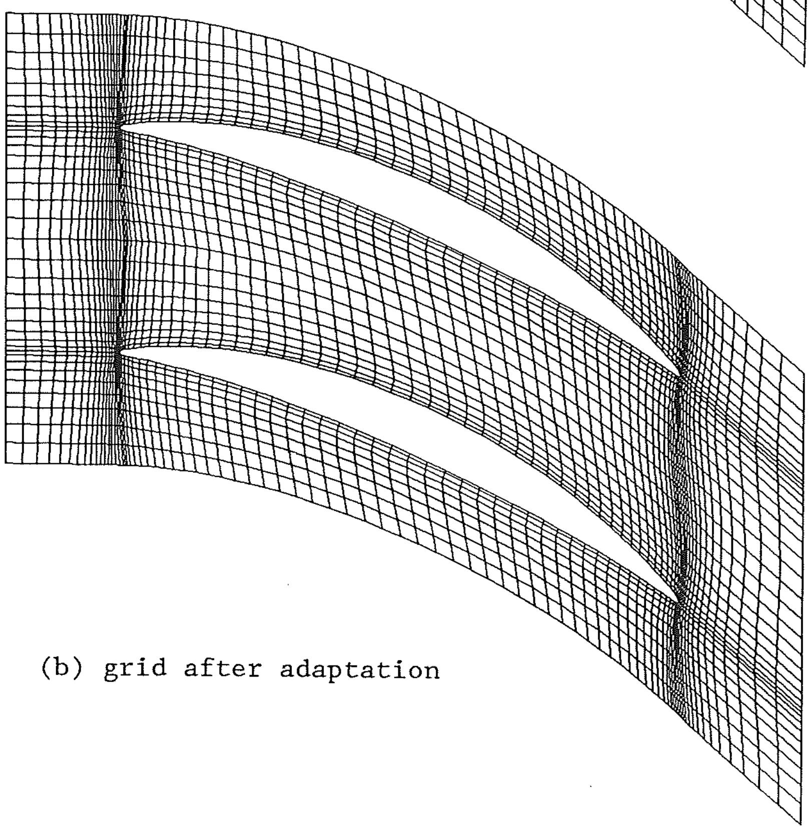
(b) grid after adaptation

Figure 8. Grid quality adaptation along wake line - reduction of grid skewness

C7



(a) grid before adaptation



(b) grid after adaptation

Figure 9. Grid quality adaptation near blade boundary - improvement of grid orthogonality